Advanced magnetic calculations for high magnetic field compact ion source

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Abstract

The design of the new advanced ECRIS requires relatively high axial and radial magnetic inductions to allow the ECR frequency increase and to take advantage of the subsequent density increase (scaling laws). The last improvements of the commercial rare earth magnets characteristics open new opportunities for ECRIS and enable to design very high hexapolar magnetic fields for next generation compact ECRIS. Moreover, the High Temperature Superconducting (HTS) wires allow designing reliable and compact axial field coils (30 K cooled) at a very effective cost. It is thus very relevant to study a compact hybrid ECRIS using high remanence magnet and HTS technologies. In such a design, the volume of the plasma chamber is a free parameter that can be adjusted to the user requirement. It can be dedicated to very high ionic current production or high charge state production, pulsed or CW operations.

This paper presents the 3D overall simulation of a 3 Tesla axial magnetic field compact ECRIS with a high radial field sextupole composed with several magnet types and reaching ~1.9 T in front of the radially magnetized magnets. This design study will lead to the building of the 28-40 GHz A-PHOENIX source at the laboratory which will deliver its first beam by the end of 2004.

1 Introduction

This paper presents a simulation study of an hybrid ECRIS based on updated permanent magnet technology to generate the radial sextupolar confinement and HTS wire technology for axial field. The 3D non-linear calculations have been performed with the RADIA[1] package of Mathematica©. The overall ECRIS structure of A-PHOENIX is drawn on figure 1, while a 3D plot of the simulation program is available on figure 2.

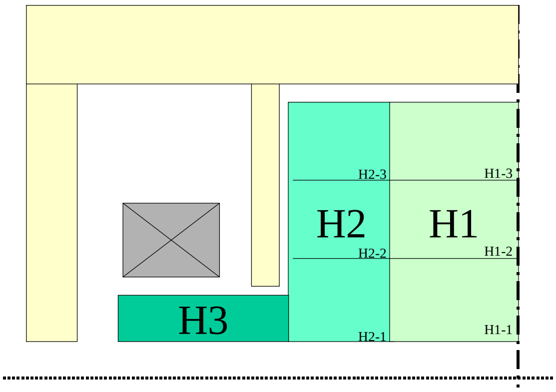

Figure 1 : sketch view of ¼ of the simulated ECRIS.

2. High Temperature Superconducting Coil

The HTS technology is today mature and reliable and can be sagely used on ECRIS. Its major advantage with respect to classical SC devices is that cooling is performed by thermal conduction with a simple industrial cryocooler with working points around 20 to 30 Kelvins. The first HTS Coils dedicated to ECRIS have been ordered to Space Cryogenics LTD by Pantechnik to be mounted on the PK-DELY ECRIS[2]. The technical datasheets for HTS superconductors wires is available on American Superconductors (AMS) web site[3]. The coils simulated in this paper relies on the "High Strength Wire" of AMS, based on Bi-2223 technology. The wire is 0.3 mm thick and 4 mm wide and can handle up to ~263 Mpa stress at 77 K. HTS coil is composed with a set of elementary pancakes with an elementary axial width of ~10 mm, a minimum inner diameter of 70 mm and a free outer one.

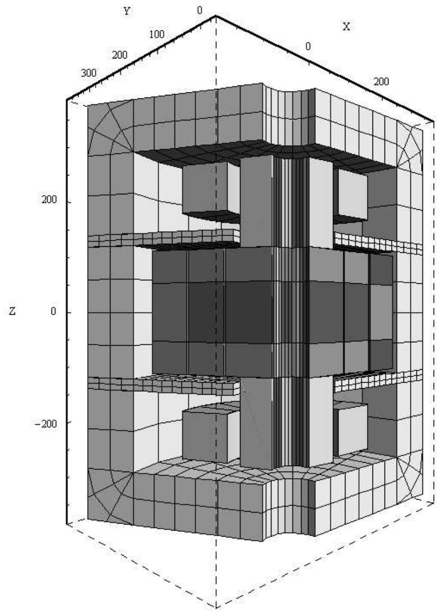

Figure 2 : Cross section of the ECRIS simulated with RADIA.

In the present paper, the simulated ECRIS is equipped with two iron shielded coils with inner and outer diameter respectively 220 mm and 370 mm and an axial height of 80 mm. The magnetic field reaches ~3 T on axis for a current density of 80 A/mm2 (see figure 3 for axial profile on ECRIS axis). The width of the mirror trap is 410 mm. The hoop stress is maximum on the inner diameter of the coil with σ=B×J×R~35 MPa. This last value is very small with respect to the critical stress of 263 Mpa. The limit for superconductivity regime comes from the maximum magnetic field wire can bear as a function of carried current for a given temperature. This point is illustrated on figure 4 where AMS wire performances for magnetic field perpendicular to the wire tape (radial magnetic field component) is plotted as a function of the critical current for several temperatures. The maximum radial magnetic field in the coils is Br~2 T for a current density of 80 A/mm2 (I~155 A in wire). The coil load line has been reported on figure 4, so one can see that a cryostat cooling down to 25-30 K will insure the superconductivity condition. The same kind of check is done with magnetic field parallel to the tape, but here, the condition is less drastic and the maximum of 4 T calculated in the coil is well below the acceptable limit at 30 K.

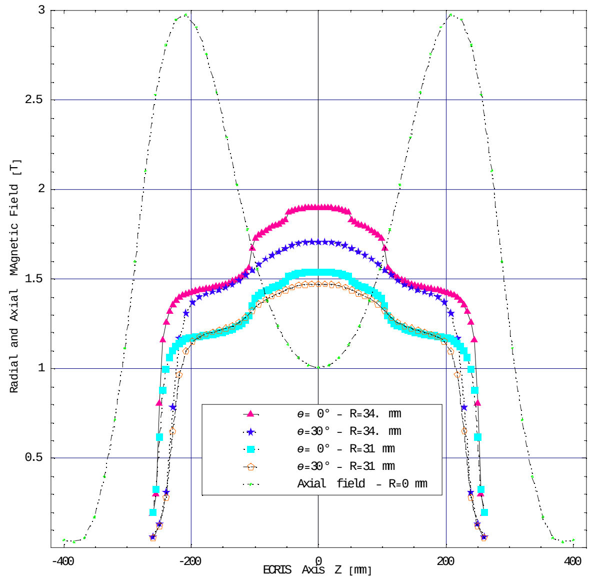

Figure 3 : Radial Magnetic confinement along the axis of ECRIS axis in front of the magnets (R=34 mm) and at the inner edge of the plasma chamber (R=31 mm). Last plot is the Axial magnetic profile at R=0 with a current density of 80 A/mm^2 in each coil.

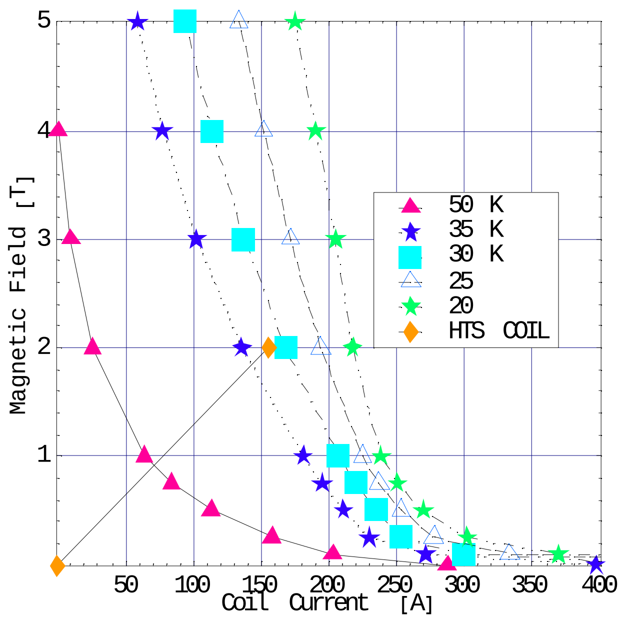

Figure 4 : AMS Bi-2223 performance for magnetic field perpendicular to the wire. See text.

3. The high magnetic field sextupole

The up to date commercial magnets offers new interesting opportunities for hallbach type sextupoles. Thus, some years ago, atomic physicists made up a 1.6 T sextupole with Vacuum Schmeltze products[4]. See Table 1 for an overview of the magnetic properties of permanent magnets from this company[5].

Table 1 : Magnet properties available fromVacuum Schmeltze datasheet[5].

Material Code	**Remanence [kG]**				**Coercivity H_{cJ} [kOe]**			
	20°C		**40°C**		**20°C**		**40°C**	
	Typ.	Min.	Typ.	Min.	Typ.	Min.	Typ.	Min.
722 HR	14.7	14.2	14.4	13.9	12	11	9.5	8.7
745 HR	14.4	14.0	14.0	13.7	15	14	12.2	11.3
633 HR	13.5	12.9	13.2	12.6	18	16	15.4	14.2
655 HR	12.8	12.2	12.6	12	23	21	20	18.7
677 HR	11.8	11.2	11.6	11	31	28	28	25.2

Below, any reference to sextupole will refer to Hallbach permanent magnet sextupole made up with 36 magnets distributed azimuthally on 2π. In this case, the magnetization axis of individual magnets with respect to the local azimuthal direction is referred here as θ_M=0, 30, 60 and 90°, where θ_M=0 stands for a magnetization axis perpendicular to the plane of symmetry of the magnet.

High coercivity magnets , such as VACODYM 655 HR, enables to build large radius sextupoles, but the usable magnetic field is quickly limited as a function of outer radius to ~1.7 T for R~250 mm. On the other hand, high remanence magnets, such as VACODYM 633 and 745 HR, enables to build very compact sextupole providing 1.3 to 1.5 T for small outer radii. But for higher radius, these last species starts to demagnetise themselves, especially for θ_M=0° near inner radius and for θ_M=90° for outer radius. Nevertheless, the inverse induction field seen by individual magnets depends strongly on θ_M and local radius in the sextupole. So it is possible to keep high remanence magnets in a large radius sextupole where the inverse field is low and use high coercivity magnets where inverse field is high. This strategy was applied for the design of the simulated sextupole. Thus, the radial field is made up with 3 types of sextupoles named H1, H2 and H3 (see figure 1). H1 contains 3 concentric crowns of permanent magnets with radii $35<R_1<115$, $119<R_2<182$, $186<R_3<250$ mm respectively. H1 extends axially from $-50<Z<50$ mm and is dedicated to maximize the radial magnetic field in the center of the plasma chamber. H2 has the same type of structure as H1 but is made up with more coercitive magnets in order to resist the additive Br component generated by the coils. It is placed symmetrically on the right and on the left of H1 at $105>|Z|>50$. Note on figures 1 and 2 the 20 mm iron disc shield between the coils and H2 to minimize the coil fringe field effects on magnets. H3 is located directly under the coil and is composed of one crown of very coercitive magnets in order to hold the main magnetic field of the coils. This structure enables to adapt accurately the magnetic induction load, magnet by magnet, in order to maximize the magnetic field in the plasma chamber. The result of this optimisation is summarized in Table 2.

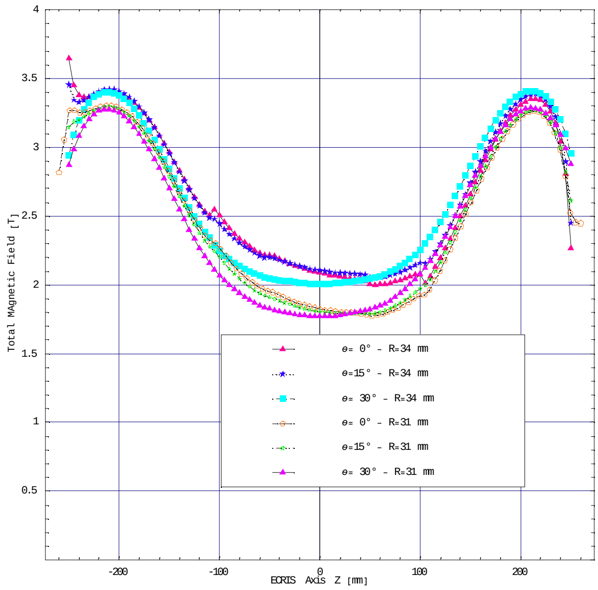

Figure 5 : Total magnetic field along the ECRIS axis for several radius and azimuthal angles.

Table 2 : Characteristics of the magnets forming the sextupoles H1, H2, H3. Hmax is the maximum magnetic induction seen by an individual magnet along its magnetization axis. (*Magnets selected as having typical coercitivity at 40°C).

θ_M [°]	**Magnet code**	**Crown #**	**H_{max} [T]**	**Magnet Load at 40°C [$H_{max}/H_{cJmin.}$]**
0	677 HR	H1-1	-1.86	-73 %
0	655 HR	H1-2	-1.35	-72 %
0	745 HR	H1-3	-0.81	-71 %
30	633 HR	H1-1	-1.3	-84% *****
30	633 HR	H1-2	-1.11	-78 %
30	745 HR	H1-3	-0.79	-70 %
60	722 HR	H1-1	-0.2	-23 %
60	722 HR	H1-2	-0.69	-79 %
60	633 HR	H1-3	-1.03	-72%
90	722 HR	H1-1	+0.5	0 %
90	722 HR	H1-2	-0.67	-77 %
90	655 HR	H1-3	-1.28	-76 %
0	677 HR	H2-1	-1.83	-72 %
0	655 HR	H2-2	-1.26	-67 %
0	745 HR	H2-3	-0.75	-66 %
30	633 HR	H2-1	-1.35	-87 % *****
30	633 HR	H2-2	-1.12	-79 %
30	745 HR	H2-3	-0.8	-71 %
60	633 HR	H2-1	-0.99	-70 %
60	745 HR	H2-2	-0.94	-83 %
60	633 HR	H2-3	-1.05	-74 %
90	745 HR	H2-1	-0.91	-80 %
90	633 HR	H2-2	-1.03	-73 %
90	655 HR	H2-3	-1.3	-69 %
0	655 HR	H3	-1.63	-87 %
30	655 HR	H3	-1.29	-77%
60	677 HR	H3	-1.87	-74%
90	677 HR	H3	-2.15	-85%

Figure 3 includes profiles of the radial magnetic field along the ECRIS axis for R=34 mm and R=31 mm for two azimuthal angles (θ=0° stands for θ_M=90° magnet type and θ=30° stands for θ_M=0°). The individual contribution of the 3 sextupoles H1,H2,H3 is clearly visible. The highest magnetic field is located under H1 : a Hall probe placed in front of θ_M=90° magnets will measure ~1.9 T, while 1.7 T is available in front of a θ_M=0° ones. The radial magnetic field in the inner edge of the plasma chamber (r=31 mm) is ~1.5 T. The slight decrease in the radial magnetic profile for |Z|>50 mm correspond to H2 with an average of ~1.7 T at r=34 mm. Then for |Z|>105 stands the H3 sextupole with still 1.4 T at r=34 mm. This radial magnetic decrease is fully balanced by the subsequent increase of the axial magnetic field toward the coils so that the total magnetic field remains smooth as it can be seen in figure 5. The magnetic intensity is superior to 2 T along the whole length of the ECRIS for r=34 mm. The magnetic intensity remains at the level of ~1.8 T at the edge of the plasma chamber. The whole sextupole is secured for a daily working temperature of ~40°C. If one can buy a sample of "typical" properties magnets and discard those with "minimum" specifications, it is possible to increase the mean magnetic induction up to 1.85 T by replacing some high coercitivity magnets by high remanence one. This second result was obtained with an inner radius of 45 mm while the outer remained at 250 mm. It underlines that this high level of magnetic field can be achieved with an arbitrary fixed inner radius.

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